SPECIAL REPORT 94-24

CRREL

Solar and Terrestrial Radiation Data From the Sleepers River Research Watershed

A Summary Report

Janet P. Hardy

August 1994

Abstract

A long-term (24-year) database of solar and terrestrial radiation, as monitored in northern Vermont, has been compiled. This extensive database is a result of cooperative efforts among many different government agencies. This report summarizes the present status of the solar and terrestrial radiation database, the instrumentation and calibration, and methods of data measurement, acquisition and analysis.

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380-89a, *Standard Practice for Use of the International System of Units,* published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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Special Report 94-24

US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

Solar and Terrestrial Radiation Data From the Sleepers River Research Watershed

A Summary Report

Janet P. Hardy

August 1994

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Janet P. Hardy, Research Hydrologist, of the Geological Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by U.S. Army Corps of Engineers Civil Works *Water Resources of Cold Regions* Research Program.

Hugh Greenan is gratefully acknowledged for his attention to detail and record-keeping during the past 25 years. That long-term consistency and his assistance has made this task possible to accomplish. The author thanks Dr. Donald Perovich and Michael Maclane for technical review of the manuscript and the following people who worked long hours on the tedious task of compiling the data: Jane Gerard, Jennifer Collyns, Rebekah Roland and Beth Gordon.

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A Summary Report

JANET P. HARDY

INTRODUCTION

The Sleepers River Research Watershed (SRRW), located in northern Vermont, has one of the longest continuous research programs and historical database for a northern temperate climate region in the United States. Hydrometeorological data have been collected at the site since 1957, and more specifically, solar radiation data have been measured since 1968. This extensive database has been used in hydrometeorological research and has been the source of numerous papers and publications (App. A). In the past, much of the research conducted in the watershed has focused on specific hydrologic events or water years and not necessarily incorporated the entire climatological database. With recent interest in improving regional predictive capabilities of the effects of a change in the global climate, this longer term (35-year) database is increasing in value. The purpose of this report is to outline the present status of the solar and terrestrial radiation database at SRRW by summarizing the instrumentation, methods of data measurement, acquisition and analysis, and the summary of available radiation data.

The Sleepers River Research Watershed has been administered by a variety of agencies over the past 35 years. In 1957, the U.S. Department of Agriculture, Agricultural Research Service (ARS) administered the SRRW. By 1966 the National Weather Service (NWS), Office of Hydrology, joined ARS in the cooperative research efforts of the watershed. In 1979, CRREL became an active participant in the operation of the watershed in cooperation with the NWS (Pangburn and McKim 1984). By 1986, the NWS and ARS had phased out activities in the watershed, and CRREL assumed the primary role. Throughout these changes in administration, the personnel involved with data collection and reduction have remained remarkably constant. Eric Anderson (NWS), Hugh Greenan (NWS/CRREL) and the University of Vermont have shared responsibility of watershed management since 1979, with Eric Anderson discontinuing his active role in 1986. In 1976, the World Meteorological Organization (WMO) acknowledged Anderson's efforts by selecting the SRRW database as one of six high-quality data sets for the WMO project on the Intercomparison of Models of Snowmelt Runoff (WMO 1982). The site was again selected in 1988 as the United States WMO location for Intercomparison of Solid Precipitation Measurement Gages.

In August 1990, the U.S. Geological Survey Water Resources Division, New England District, in cooperation with CRREL, began an extensive investigation of the water, energy, and biogeochemical budgets (WEBB) at the Sleepers River Research Watershed. This project is designed to improve the understanding of basic watershed processes in northern forested regions and, in particular, one affected by a seasonal snowcover. The importance of a reliable database, and in particular radiation data, is central to the understanding of energy driven processes and is the subject of this report. Harding (1986) notes that in southern Norway, 56% of the energy required for snowmelt is provided by the net radiation (Q^*), illustrating the importance of radiation data to the hydrologic response of melting snow.

Literature on short- and long-wave radiation data is not always consistent in the use of symbols and definitions related to the many components of radiation. The symbols used in this report (Table 1) are based on those utilized by Oke (1987), Phillips et al. (1988), and Prowse and Ommanney (1990).

Table 1. Symbols and respective radiation components as used in this report. All units of radiation are in W/m^2.

Symbol	*Radiation component*
K_{in}	incoming short-wave (global or solar), includes direct and diffuse
K_{ref}	reflected short-wave (global or solar)
K^*	net short-wave: $K^* = (K_{in}) - (K_{ref})$
L_{in}	incoming long-wave (terrestrial)
L_{out}	outgoing long-wave (terrestrial)
L^*	net long-wave: $L^* = (L_{in}) - (L_{out})$
Q_{in}	total hemispheric
Q_{out}	total outgoing
Q^*	net all-wave: $Q^* = K^* + L^*$

SITE LOCATION AND DESCRIPTION

The Sleepers River Research Watershed is located in rural Caledonia County, Vermont (Fig. 1). The SRRW is a 111.4-km^2 subwatershed of the Passumpsic River Watershed, which is part of the Connecticut River basin. The SRRW consists of 16 subwatersheds labeled W-1 through W-16 in Figure 1. The watershed varies from rolling hills to mountainous terrain ranging from 201–790 m above sea level (Pionke et al. 1986). Sixty-seven percent of the watershed is forested, while the remaining 33% is pasture and hayland (Pionke et al. 1986). The land use patterns within the watershed have not changed significantly over the 35-year period of data collection, but some forest composition has changed because of logging (Anderson et al. 1977 and Greenan

* H. Greenan, Meteorologic Technician, Sleepers River Research Watershed, Danville, Vermont, personal communication 1991–93.

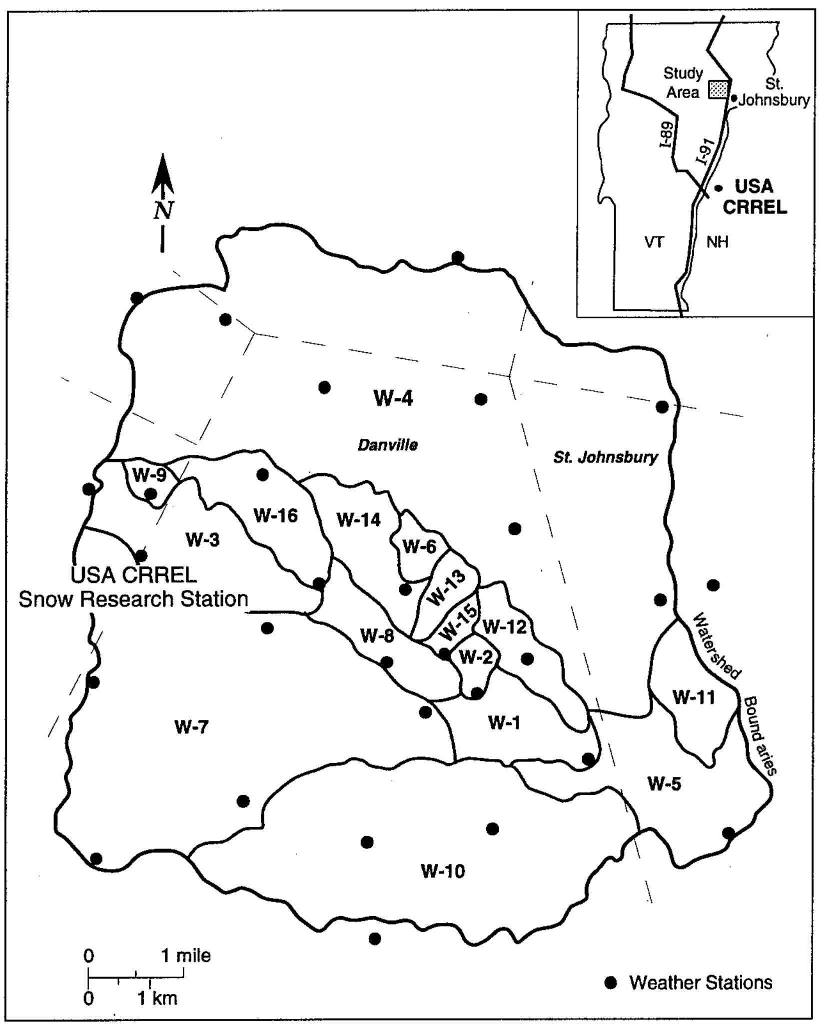

Figure 1. Location of the Sleepers River Research Watershed in Danville, Vermont. The 16 subwatersheds are labeled W-1 through W-16.

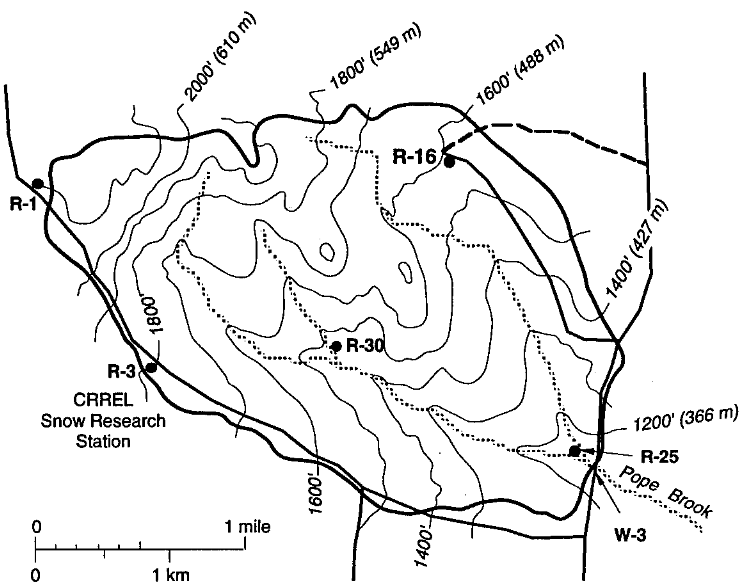

Figure 2. Location of W-3 Research Watershed. The CRREL Snow Research Station (Townline Station) is the site of the radiation instrumentation in this report.

1991–93*). The climate of northeastern Vermont is characterized by long, cold winters and cool summers with a mean annual temperature of 6°C. Annual precipitation totals range from 880–1270 mm/year, with more than 25% measured as water equivalent snowfall. Snowcover persists from early December through late March (Anderson et al. 1977).

In the west-central portion of the SRRW, at 550 m msl, is a small (8.4-km^2) subwatershed (W-3) with a complete meteorological station (Fig. 2). This station is now known as the Townline Station or the CRREL Snow Research Station, and is the site of solar and terrestrial radiation measurements. The meteorological and hydrological parameters currently monitored at the Townline Station include temperature, precipitation, incoming and reflected shortwave and incoming and outgoing long-wave radiation, wind speed and direction (3- and 6-m height), relative humidity and dew point, snow depth, density and snow water equivalence (SWE), soil moisture, temperature and frost depth, and snow cover lysimeter outflow.

RADIATION INSTRUMENTATION

The history of the specific radiometers used at the Townline Station is summarized in Table 2. The reliability of a radiometer depends on the available technology, as well as proper field maintenance and calibration. Hard copies of the data contain notes regarding times when radiometers are covered by snow, ice or frost or when instrumentation is malfunctioning.

Table 2. Radiometers used at the Townline Station, SRRW, 1968–present. Eppley instruments are further described in Eppley Laboratory, Inc. (1986).

Parameter	*Instrument*
K_{in}	a. Dec. 1968–May 1970 Eppley Laboratory, 50-jct., temperature compensated, black and white concentric ring, bulb pyranometer.
	b. Jun. 1970–present Eppley Laboratory, Model 2 temperature compensated precision pyranometer (PSP)
K_{ref}	a. Dec. 1968–Feb. 1973 Eppley Laboratory, 50-jct., temperature compensated, black and white concentric ring, bulb pyranometer.
	b. Mar. 1973–present Eppley Laboratory, Model 2 temperature compensated precision pyranometer (PSP)
L_{in}	a. Oct. 1971–Mar. 1972, Mar. and Apr. 1973 Eppley pyrgeometer (hemispherical infrared radiometer) with KRS-5 dome
	b. May 1986–present Same instrument, new dome Eppley precision infrared radiometer (PIR) with silicon dome
L_{out}	a. Jan. 1988–present Bought in 1971, not used as L_{out} until 1988. Eppley precision infrared radiometer (PIR) with silicon dome
Q_{in}	a. Dec. 1968–Sep. 1971; and Apr. 1972–Feb. 1973 Ventilated Gier and Dunkle type total hemispherical radiometer (Beckman-Whitley and Thornwaite). Although Q_{in} was measured, data were reduced to L_{in}.
	b. Nov. 1979–Apr. 1986 Swissteco pyrradiometer, serial no. 7067

Calibration of pyranometers

The two Eppley pyranometers (precision spectral pyranometers—PSP) operating at SRRW have been the source of shortwave radiation data since 1970 (K_{in}) and 1973 (K_{ref}). When an Eppley PSP leaves the Eppley Laboratory, it is assigned a calibration constant (mV/cal cm^2 min) tested against the World Radiation Reference (WRR). This constant is used in the calculation of the radiation value either manually or by programming the constant into the data logger. To ensure proper calibration, the radiometers have either been returned to the Eppley Laboratory for recalibration or, more often, site calibrated using techniques described later in this section.

Table 3. Calibration constants determined by Eppley Laboratory for the PSPs used at SRRW and the percent change. Constants are in mV/cal cm^2 min.

Calibration date	*SN 10276F4*	*SN 10277F4*
2/20/70	4.98	4.92
9/9/76	4.76	—
6/11/91	4.41	—
10/8/91	—	4.69
10/6/93	—	4.57
% change	7.4	4.7

In June 1991, the PSP used to measure incoming shortwave radiation (SN 10276F4) was sent to the Eppley Laboratory for recalibration and was returned with a lower calibration constant than had previously been used (Table 3). Similarly, the PSP used for reflected shortwave radiation (SN 10277F4) showed a similar discrepancy in its calibration constant when returned from Eppley Laboratory in October 1991 (Table 3). This decrease in calibration constants for both pyranometers is due to the graying of the optical black lacquer over time (Kirk 1993*). The percentage change in calibration constants over time for the PSP with SN 10277F4 (Table 3) is small and approaches the accuracy tolerance of the sensor (2.5–4.5%). Additionally on 1 April 1977 the calibration traceability changed from the International Pyrheliometric Scale of 1956 (IPS 1956) to the absolute scale (SI), resulting in an increase of 2.1% (Eppley 1986). The greater percentage of change, 7.4%, in calibration constants for the PSP (SN 10276F4) is problematic. Conversations with the President of Eppley Laboratory resulted in a recommendation to make no adjustments to the data from either PSP, as the decay in the constant for PSP with SN 10277F4 is reasonable for a 21-year period. To adjust data from the PSP SN 10276F4 would be difficult, due to the uncertainty of the actual sensor decay curve through time. Therefore, no adjustments were made to the data.

The long-term meteorological technician (H. Greenan) has recommended some data adjustments assuming a linear decay in the calibration constant from 1980 to 1991, which are discussed in Appendix B. Radiation data from days noted as "clear sky days" during the periods were used as an additional check on the adjustment of the calibration constant. Consistency of data was validated by comparing the expected clear sky values of insolation with the actual values obtained. This technique required comparison of values of insolation on a cloudless day with those normally expected under clear skies for the latitude and time of year (Anderson et al. 1977). Another method used to confirm reliability of radiation measurements is to place both PSPs in the upright position adjacent to each other and check for agreement within 3% between respective sensor output (PSP SN 10276F4 was considered by H. Greenan as the more reliable radiometer). This technique was frequently employed during all, or part of, the snow-free seasons.

Calibration of pyrgeometers

The Swissteco radiometer was used to measure total hemispheric radiation from 1979–1986. The Swissteco had a polyethylene dome that was routinely inspected for "dimples" and purged on a continual basis. The Swissteco was replaced in 1986 by an Eppley pyrgeometer with a silicon dome (precision infrared radiometers—PIR) able to measure either incoming or outgoing long-wave radiation. In 1986, both PIRs were sent to Eppley Laboratory. The PIR SN 11307F3 was returned due to a lightning strike and repaired, and a silicon dome was installed, but the PIR was not calibrated. The PIR SN 11315F3 received a new thermopile and was recalibrated. Since January 1988, the use of two PSPs and two PIRs, where one of each was inverted, allowed calculation of all radiation parameters: K^*, L^*, Q_{in}, Q_{out} and Q^*. Fundamental calibration of Eppley PIRs is based on their exposure to an ideal blackbody radiator (Eppley Laboratory 1986) and is conducted in the Eppley Lab where each PIR is assigned a calibration constant (Table 4). Field calibration checks were also employed at SRRW, using an Eppley black body cavity, where the calibration constant was monitored and/or adjusted as required.

*G. Kirk, President, Eppley Laboratory, Newport, Rhode Island, personal communication 1993.

Table 4. Calibration constants determined by Eppley Laboratory for the PIRs used at SRRW. Constants are in mV/cal cm^2 min.

Calibration date	*SN 11307F3*	*SN 11315F3*
9/71	4.97	4.27
11/72	4.63	4.32
9/73	4.39	—
12/86	—	3.00
1/92	2.49	—

METHODS OF DATA ACQUISITION

Radiation data, as well as other meteorological data, have been recorded on assorted data loggers during the past 24 years. For the entire period of record, measurements of radiation were taken every minute and summed on the hour, yielding hourly irradiation (energy/area per unit time) values. Beginning in 1968, data were collected on electronic volt-time integrators (Lectrocount) and subsequently on a voltage numerical integrator (VNI). These data were reduced on a regular basis until 1978, and the data stored on the original strip tapes. Approximately 7.5 years of VNI data from data tapes required hand entering into a spreadsheet program. Neither the Lectrocount nor the VNI systems were capable of converting values of millivolts to radiation units, and such additional conversions were required of this data (App. C). In March 1986, the VNI was replaced by a Kaye data logger capable of data reduction and of providing measurements of radiation in langleys. Most of the data from the Kaye data logger were in hard copy format and required extensive computer scanning and editing, while a lesser amount of the Kaye data had previously been reduced and existed on computer diskettes. Beginning December 1988, a Campbell Scientific Instrument (CSI) model 21X micro-logger was installed. This micro-logger is a user programmable, battery operated microcomputer which either stores data in the data logger or on a storage module and is later downloaded onto a personal computer. Hard copies of 21X data also exist and were used to fill any gaps in the data record.

STATUS OF RADIATION DATA AT TOWNLINE STATION

Due to the many agencies involved with data collection at the SRRW and the sometimes limited funding available to conduct snow hydrology research, gaps exist in the database. Some of the smaller gaps are a result of power outages, lightning strikes, and human error (i.e., unfamiliarity with the new data logger etc.), while larger gaps occurred during major equipment failures. Appendix D summarizes the entire database beginning in December 1968 and continuing through 1992. The radiation parameters measured and the successive changes through time are presented. Appendix E summarizes the missing radiation data from 1978–1992.

Data organization and analysis

The ultimate objective of this project was to collect, reduce and standardize the 24 years of radiation data from the SRRW and to make the database accessible to researchers. This task involved the efforts of several people in locating the data, putting data into a common computer data manager and conversion of all data to common SI units (watts per square meter—W/m^2). Lectrocount and VNI data were converted from millivolts, while Kaye and 21X data were converted from langleys. The calculations involved in these conversions are presented in Appendix C. Data are available on a daily basis with values as recorded every hour. Summary statistics performed on the SRRW database include:

1. Hourly totals as recorded by data logger (K and L)
2. Daily totals (K and L)
3. Monthly mean (K and L).

Accuracy and reliability of data

All radiation data from the SRRW have been analyzed to test for accuracy and reliability, with bad data being omitted and questionable data delineated with separate notation. Methods of checking reliability consisted of cross reference of SRRW data with other short-term (6- to 10-yr) radiation databases. These preexisting radiation databases include data from the CRREL Meteorological Field Station in Hanover, New Hampshire (Bates 1984) and previously reduced SRRW data from 1968–74 (Anderson et al. 1977). Incoming shortwave radiation values obtained from SRRW on a clear sky day were compared with the clear sky solar radiation curve for the Townline Station (Anderson et al. 1977). All radiation data were plotted on monthly graphs and checked for outliers. Additionally, at all stages in the reduction/analysis process, data were consistently checked against an acquired understanding of reasonable hourly and/or daily values of the radiation components.

Problems with data collection were inevitable dealing with radiometers in cold climates, as snow-

fall accounts for a significant percent of the precipitation. Shortwave radiation penetration through snow decreases exponentially with an increase in snow depth (Oke 1987). This accounts for the difficulty in obtaining an accurate measure of insolation when radiometers are snow, ice or frost covered and not constantly wiped clean. Values of daytime incoming shortwave radiation, when radiometers were snow, ice or frost covered, were adjusted based on known snow albedo determinations. The surface albedo was calculated prior to the event and immediately after radiometers were cleared of snow, ice or frost. The mean value of the two albedo measurements was used in conjunction with the reflected shortwave radiation value to approximate the incoming shortwave radiation under snow, ice or frost covered radiometers.* Estimated values of insolation are delineated by separate notation.

Other notable changes or corrections were made prior to completion of the SRRW radiation database. During summer periods when both pyranometers were measuring incoming shortwave radiation, data from the pyranometer (SN 10276F4) only were used in analysis. Pyranometers have the same calibration constant in both the upright and inverted positions. Also, the data recorded on the volt–time integrator (1968 to April 1986) give nighttime, incoming shortwave (K_{in}) radiation values greater or less than zero. As nonzero values of K_{in} are not possible at night, corrections were made to zero nighttime values and to adjust daytime values. This procedure involved subtracting the mean of the K_{in} value just prior to sunrise and immediately after sunset, from the entire day and zeroing all other nighttime measurements.

CONCLUSIONS

This report is the result of locating, collecting, compiling and standardizing the 24-year record of radiation data from the Townline Station at Sleepers River Research Watershed. The status of the radiation data is presented along with employed quality control techniques. The historical radiation database is a unique data set, given the long-term record involved, its location in a temperate, cold region area, and its acknowledged high quality. This data set is invaluable to the studies of water, energy, and biogeochemical budgets and has implications for global change research.

* H. Greenan, Meteorologic Technician, Sleepers River Research Watershed, personal communication 1991–93.

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APPENDIX B: POTENTIAL ADJUSTMENTS TO SHORTWAVE RADIATION DATA

Possible adjustments were determined for all incoming shortwave radiation data from April 1980 to July 1991 by multiplying the original radiation value in langleys by an estimated multiplier. The multiplier used to adjust the radiation data was calculated by the on-site meteorological technician, Hugh Greenan. A linear decay in the calibration constant was assumed during the 11-year period of adjustment, with the greatest decay occurring during the summer months. For this reason, each multiplier used for data adjustment was assigned to the data for a one-year period beginning 30 April.

Adjustment factors on PSP (serial number 10276F4):

calibration constant as of 9-23-76: 4.76 mV/calc m^2 min
calibration constant as of 6-27-91: 4.41 mV/calc m^2 min

Date of adjustments			Adjustment factor
4-30-80	to	4-30-81	1.00668
4-30-81	to	4-30-82	1.01337
4-30-82	to	4-30-83	1.02005
4-30-83	to	4-30-84	1.02674
4-30-84	to	4-30-85	1.03342
4-30-85	to	4-30-86	1.04011
4-30-86	to	4-30-87	1.04679
4-30-87	to	4-30-88	1.05348
4-30-88	to	4-30-89	1.06016
4-30-89	to	4-30-90	1.06684
4-30-90	to	5-24-91	1.07353

Adjustment factors on PSP (serial number 10277F4):

calibration constant as of 9-23-76: 4.92 mV/cal cm^2 min
calibration constant as of 11-4-91: 4.42* mV/cal cm^2 min

Date of adjustments			Adjustment factor
4-30-80	to	4-30-81	1.00924
4-30-81	to	4-30-82	1.01848
4-30-82	to	4-30-83	1.02772
4-30-83	to	4-30-84	1.03695
4-30-84	to	4-30-85	1.04619
4-30-85	to	4-30-86	1.05543
4-30-86	to	4-30-87	1.06467
4-30-87	to	4-30-88	1.07391
4-30-88	to	4-30-89	1.08315
4-30-89	to	4-30-90	1.09239
4-30-90	to	4-30-91	1.10163

* constant determined by H. Greenan

APPENDIX C: RADIATION DATA CONVERSIONS

Equations used to convert radiation data in millivolts to Ly/hr and Ly/hr to W/m^2:

$$
\begin{aligned}
V &= \text{output value in volts} \\
CC &= \text{calibration constant (mV/cal cm}^2\text{ min)} \\
PT &= \text{plate temperature output (mV)} \\
Q_{in}(u) &= \text{unadjusted } Q_{in} \text{ (Ly/hr)} \\
BIAS &= \text{bias in plate temperature} \\
TPC &= \text{plate temperature in degrees Celsius} \\
TPK &= \text{plate temperature in kelvins} \\
ADJ\text{-}1 &= \text{adjustment for copper thermocouple} \\
ADJ\text{-}2 &= \text{adjustment factor} \\
SBL &= \text{Stefan-Boltzmann law}
\end{aligned}
$$

To obtain K_{in} or K_{ref}:

$$
\begin{aligned}
\text{output } V/1000 &= \text{mV} \\
\text{mV}/CC \times 60 &= \text{Ly/hr}
\end{aligned}
$$

To obtain L_{in}:

$$
\begin{aligned}
Q_{in}(u) &= (((\text{mV-800})/100)/CC) \times 60 \\
BIAS &= (PT/1000) - 8 \\
TPC &= (-0.0385 + 0.00148 + (0.000172) \times BIAS\,)/\ 0.000086 \\
TPK &= TPC + 273.15 \\
ADJ\text{–}1 &= (-0.00025 \times TPC) + 1.005 \\
ADJ\text{–}2 &= Q_{in}(u) \times ADJ\text{–}1 \\
SBL &= 5.67 \times 10^{-8}\ \text{W m}^{-2}\,\text{K}^{-4} \times TPK^4 \\
Q_{in}\,(\text{Ly/hr}) &= ADJ\text{-}2 \times SBL \\
L_{in} &= Q_{in} - K_{in}.
\end{aligned}
$$

To convert Ly/hr to W/m^2:

1 Ly/hr = 11.622 W/m^2.

APPENDIX D. SUMMARY OF TOWNLINE STATION RADIATION DATA.

Year	*Month*	*Dates*	*Recorder*	K_{in}	K_{ref}	K^*	L_{in}	L_{out}	L^*	Q_{in}	Q^*
1968	Dec	complete	White bk	*	*	C	*			C	
To											
1969	Apr	complete	White bk	*	*	C	*			C	
	Nov	complete	White bk	*	*	C	*			C	
To											
1974	Sep	complete	White bk	*	*	C	*			C	
1968	Oct	complete	WMO	*							
To											
1978	Sep	complete	WMO	*							
	Oct	complete	VNI	*	*	C	C			*	
	Nov	complete	VNI	*	*	C	C			*	
	Dec	complete	VNI	*	*	C	C			*	
1979	Jan	complete	VNI	*	*	C				*	
	Feb	complete	VNI	*	*	C				*	
	Mar	complete	VNI	*	*	C				*	
	Apr	complete	VNI	*	*	C				*	
	May	complete	VNI	*	*	C				*	
	Jun	complete	VNI	*	*	C				*	
	Jul	complete	VNI	*	*/	C/				*	
	Aug	complete	VNI	*						*	
	Sep	complete	VNI	**/						*	
	Oct	complete	VNI	**						*	
	Nov	complete	VNI	**/	/*	/C				*	
	Dec	complete	VNI	*	*	C				*	
1980	Jan	complete	VNI	*	*	C	C			*	
	Feb	complete	VNI	*	*	C	C			*	
	Mar	complete	VNI	*	*	C	C			*	
	Apr	complete	VNI	*	*	C	C			*	
	May	complete	VNI	**			C			*	
	Jun	complete	VNI	**			C			*	
	Jul	complete	VNI	**			C			*	
	Aug	complete	VNI	**			C			*	
	Sep	complete	VNI	**			C			*	
	Oct	complete	VNI	**							
	Nov	complete	VNI	**/	/*	/C	C			*	
	Dec	complete	VNI	*	*	C	C			*	
1981	Jan	complete	VNI	*	*	C	C			*	
	Feb	complete	VNI	*	*	C	C			*	
	Mar	complete	VNI	*	*	C	C			*	
	Apr	complete	VNI	*	*	C	C			*	
	May	complete	VNI	*			C			*	
	Jun	complete	VNI	*			C			*	
	Jul	complete	VNI	*			C			*	
	Aug	complete	VNI	*			C			*	
	Sep	complete	VNI	*			C			*	
	Oct	complete	VNI	*			C			*	
	Nov	complete	VNI	*			C			*	
	Dec	complete	VNI	*	*	C	C			*	

Year	Month	Dates	Recorder	K_{in}	K_{ref}	K^*	L_{in}	L_{out}	L^*	Q_{in}	Q^*
1982	Jan	complete	VNI	*	*	C	C			*	
	Feb	complete	VNI	*	*	C	C			*	
	Mar	complete	VNI	*	*	C	C			*	
	Apr	complete	VNI	*	*	C	C			*	
	May	complete	VNI	*	*/	C/	C			*	
	Jun	complete	VNI	*			C			*	
	Jul	complete	VNI	*			C			*	
	Aug	complete	VNI	*			C			*	
	Sep	complete	VNI	*			C			*	
	Oct	complete	VNI	*			C			*	
	Nov	complete	VNI	*	*	C	C			*	
	Dec	complete	VNI	*	*	C	C			*	
1983	Jan	complete	VNI	*	*	C	C			*	
	Feb	complete	VNI	*	*	C	C			*	
	Mar	complete	VNI	*	*	C	C			*	
	Apr	complete	VNI	*	*	C	C			*	
	May	complete	VNI	*	*	C	C			*	
	Jun	complete	VNI	**			C			*	
	Jul	complete	VNI	**			C			*	
	Aug	complete	VNI	**							
	Sep	complete	VNI	**			/C			/*	
	Oct	complete	VNI	**			C			*	
	Nov	complete	VNI	**			C			*	
	Dec	complete	VNI	*	*	C	C			*	
1984	Jan	complete	VNI	*	*	C	C			*	
	Feb	complete	VNI	*	*	C	C			*	
	Mar	complete	VNI	*	*	C	C			*	
	Apr	complete	VNI	*	*	C	C			*	
	May	complete	VNI	*			C			*	
	Jun	complete	VNI	**			C			*	
	Jul	complete	VNI	**			C			*	
	Aug	complete	VNI	**			C			*	
	Sep	complete	VNI	**			C			*	
	Oct	complete	VNI	**			C			*	
	Nov	complete	VNI	**/	/*	/C	C			*	
	Dec	complete	VNI	*	*	C	C			*	
1985	Jan	complete	VNI	*	*	C	C			*	
	Feb	complete	VNI	*	*	C	C			*	
	Mar	complete	VNI	*	*	C	C			*	
	Apr	complete	VNI	*	*	C	C			*	
	May	complete	VNI	**			C			*	
	Jun	complete	VNI	**			C			*	
	Jul	complete	VNI	**			C			*	
	Aug	complete	VNI	**			C			*	
	Sep	complete	VNI	**			C			*	
	Oct	complete	VNI	**			C			*	
	Nov	complete	VNI	**/	/*	/C	C			*	
	Dec	complete	VNI	*	*	C	C			*	

Year	*Month*	*Dates*	*Recorder*	K_{in}	K_{ref}	K^*	L_{in}	L_{out}	L^*	Q_{in}	Q^*
1986	Jan	complete	VNI	*	*	C	C			*	
	Feb	complete	VNI	*	*	C	C			*	
	Mar	complete	VNI	*	*	C	C			*	
	Apr	complete	VNI	*	*	C	C/*			*/C	
bad>19	May	8–28	Kaye	*			*			C	
bad ?	Jun	26–30	Kaye	*							
	Jul	complete	Kaye	**			*			C	
bad ?	Aug	3–6; 12–29	Kaye	**/							
	Sep	N/A									
	Oct	8–27	Kaye	*							
	Nov	1–8	Kaye	*							
	Dec	4–31	Kaye	*							
1987	Jan	1–15; 21–31	Kaye	/*	*	/C					
	Feb	complete	Kaye	*	*	C					
	Mar	complete	Kaye	*	*	C					
	Apr	1–28	Kaye	*	*	C					
	May	5–28	Kaye	*	*	C	/*			/C	
	Jun	9–30	Kaye	**			**			C	
	Jul	complete	Kaye	**			**			C	
	Aug	complete	Kaye	**			*			C	
	Sep	1–18; 21–30	Kaye	**			*			C	
	Oct	1–4; 12–21	Kaye	**			*			C	
	Nov	N/A	–	–	–	–	–	–	–	–	
	Dec	12–31	Kaye	*	*	C					
1988	Jan	complete	Kaye	*	*	C	/*	/*	C	C	C
	Feb	1–26	Kaye	*	*	C	*	*	C	C	C
*	Mar	complete	Kaye	*	*	C	*	*	C	C	C
	Apr	1–12	Kaye	*	*/	C/	*	*/	C/	C/	C
	May	N/A	–	–	–	–	–	–	–	–	–
	Jun	1–12	Kaye	*	*	C	–	–			
	Jul	N/A	–	–	–	–	–	–	–	–	–
	Aug	N/A	–	–	–	–	–	–	–	–	–
	Sep	13–30	Kaye	*	*	C					
	Oct	1–17; 25–31	Kaye	*	*	C					
	Nov	1–5	Kaye	*	*	C					
	Dec	23–31	21X	–	–	–	–	–	–	–	–
1989	Jan	complete	21X	/*	/*	/C	/*	/*	/C	/C	/C
	Feb	complete	21X	*	*	C	*	*	C	C	C
	Mar	complete	21X	*	*	C	*	*	C	C	C
	Apr	complete	21X	*	*	C	*	*	C	C	C
	May	complete	21X	*	*/	C/	*/	*/	C/	C/	C/
	Jun	12–30	21X	**							
	Jul	complete	21X	**							
	Aug	complete	21X	**							
	Sep	complete	21X	**							
	Oct	complete	21X	**							
	Nov	complete	21X	**							
	Dec	complete	21X	**							

Year	Month	Dates	Recorder	K_{in}	K_{ref}	K^*	L_{in}	L_{out}	L^*	Q_{in}	Q^*
1990	Jan	complete	21X	**/	/*	/C	/*	/*	/C	/C	/C
	Feb	complete	21X	*	*	C	*	*	C	C	C
	Mar	complete	21X	*	*	C	*	?	C	C	C
	Apr	complete	21X	*	*	C	*	*	C	C	C
	May	complete	21X	*	*	C	*	*	C	C	C
	Jun	complete	21X	*	*	C	*/	*/	C/	C/	C/
	Jul	complete	21X	*	*	C					
	Aug	complete	21X	*	*	C					
	Sep	complete	21X	*	*	C					
	Oct	complete	21X	*	*	C					
	Nov	complete	21X	*	*	C					
	Dec	complete	21X	*	*	C	/*	/*	/C	/C	/C
1991	Jan	complete	21X	*	*	C	*	*	C	C	C
	Feb	complete	21X	*	*	C	*	*	C	C	C
	Mar	complete	21X	*	*	C	*	*	C	C	C
	Apr	complete	21X	*	*	C	*/	*	C	C	C
	May	complete	21X	*			*			C	
	Jun	complete	21X	**			**			C	
	Jul	complete	21X	**							
	Aug	complete	21X	**						C	
	Sep	complete	21X	**							
	Oct	complete	21X	**							
	Nov	complete	21X	**							
	Dec	complete	21X	**	*	C	*	*	C	C	C
1992	Jan	complete	21X	*	*	C	*	*	C	C	C
	Feb	complete	21X	*	*	C	*	*	C	C	C
	Mar	complete	21X	*	*	C	*	*	C	C	C
	Apr	complete	21X	*	*	C	*	*	C	C	C
	May	complete	21X	*	*	C	*	*	C	C	C
	Jun	complete	21X	*	*/		*/	*/		C	
	Jul	complete	21X	**							
	Aug	complete	21X	**						C	
	Sep	complete	21X	**							
	Oct	complete	21X	**							
	Nov	complete	21X	**			*/	*/			
	Dec	complete	21X	*	*	C	*	*	C	C	C

* = data were measured
C = value can be calculated
/* = data for beginning portion of month are missing
*/ = data for latter portion of month are missing
** = both radiometers are reading K_{in}

APPENDIX E: TOWNLINE STATION MISSING RADIATION DATA: 1978–1992.

Year	*Month*	*J.D.*	*Time*	*to*	*J.D.*	*Time*	*Missing parameter*
1978	Nov	328	1500	to	331	1600	No radiation data
1979	Feb	37	1700	to	49	100	No L_{in}
		39	1800	to	40	1100	No radiation data
	Mar	69	200	to		500	No L_{in}
		69	2100	to	71	1100	No radiation data
	Apr	113	700	to		1000	No K_{ref}
	Jul	206	1000	to		1100	No L_{in}
	Aug	225	300	to		1300	No L_{in}
		227	1300	to	228	1700	No L_{in}
		228	1300	to		1600	No radiation data
	Sep	245	2300	to	247	1000	No radiation data
		257	1700				No K_{in}
	Oct	290	2400	to	291	900	No L_{in}
	Nov	307	100	to		2400	No L_{in}
		332	200	to		900	No L_{in}
		334	1200				No K_{in}
	Dec	342	1300	to		1500	No L_{in}
1980	Jan	28	1300	to		2400	No L_{in} (one of two missing)
	Feb	48	500				No radiation data
		48	700				No L_{in}
		48	1000	to	48	1300	No L_{in}
		48	2300	to	49	400	No radiation data
		50	700	to		1200	No radiation data
		52	1300	to		1700	No K_{ref}
		60	900	to		2400	No L_{in}
	Mar	91	2100	to		2400	No L_{in}
	May	124	2300				No radiation data
		125	400				No L_{in}
		144	1500	to		1700	No radiation data
	Jun	153	700	to		900	No radiation data
		181	1800	to		2000	No radiation data

Year	Month	J.D.	Time	to	J.D.	Time	Missing parameter
1980	Jul	191	1100				No K_{in} (#2)
		191	1200	to		1500	No radiation data or adjusted data
		195	200				No radiation data
		214	100	to		2400	No radiation data
	Aug	218	1700	to	219	1100	No radiation data
		224	800	to		1100	No L_{in}
		225	1100	to		1400	No radiation data
		225	2100	to	226	1000	No radiation data
		231	1200				No K_{in}
		243	2200	to	244	900	No radiation data
	Sep	246	1400	to		1700	No L_{in}
		246	1400	to		1600	No L_{in}
1981	Feb	40	100	to	59	1700	No L_{in}
	Apr	106	1900				No K_{ref}
		107	600				No K_{ref}
		120	1300	to		1600	No K_{ref}
	May	125	1100	to		1400	No L_{in}
		143	1400	to		1600	No L_{in}
		143	2000	to	144	700	No L_{in}
		149	800	to		1200	No L_{in}
	Jun	157	1200	to		2200	No radiation data
		159	900				No radiation data
		162	1300				No radiation data
	Jul	185	1300	to	186	400	No L_{in}
		186	900	to		1400	Sporatic L_{in}
		187	100	to	188	1300	Sporatic L_{in}
		190	1700	to		2100	Sporatic L_{in}
		196	800				No radiation data
	Aug	241	2400	to	242	1600	No radiation data—printer malfunction
	Oct	298	100				No radiation data
	Nov	324	800	to		1300	No data
		327	1200	to	334	1400	No K_{in} on one radiometer
1982	Mar	67	1000				No L_{in}
	Apr	92	1400	to		1600	No *PT* or Q_{in}.
		102	400	to		700	No *PT* or Q_{in}.
	May	138	1100	to	147	1500	No K_{ref}—disconnected
		139	1700	to		2200	No radiation data—power outage
		147	800	to		1000	No L_{in}

Year	*Month*	*J.D.*	*Time*	*to*	*J.D.*	*Time*	*Missing parameter*
1982	Jul	212	1700	to		1900	No radiation data
	Aug	225	1000				No L_{in} and 1 of 2 K_{in} missing
		237	1900	to	238	1100	No radiation data—power outage
		238	1500				No radiation data—power outage
	Sep	260	1000				No L_{in} and 1 of 2 K_{in} missing
	Nov	305	1400	to	306	1300	No K_{ref}
		305	1800	to	306	1300	No radiation data
	Dec	346	2400				No radiation data
1983	Jan	13	1400	to		1500	No L_{in}
		14	1400				No radiation data
	Feb	32	1400	to	33	1200	No radiation data
	Jun	158	1100	to	160	1100	No radiation data
		166	1600				No radiation data
		168	1700	to		2100	No radiation data
		181	1600	to		2400	No K_{ref}—disconnected
	Jul	183	1300				No radiation data
		183	1500				No radiation data
		193	2300				No L_{in}
		196	2000				No L_{in}
		202	1400	to		1600	No L_{in}
		202	2300	to	203	1700	No L_{in}
		203	100	to		1100	No radiation data
		203	2000	to		2400	No radiation data
		204	900	to		1300	No L_{in}
		204	1500	to	206	1000	No radiation data
		206	2200	to	208	1400	No radiation data
		208	1400	to	212	2400	No L_{in}
		210	1300	to		1500	No radiation data
	Aug	213	100	to	243	2400	No L_{in}
	Sep	244	100	to	252	1200	No L_{in}
		255	400	to		1000	No radiation data
		263	1200	to		1400	No radiation data
		270	900				No L_{in}
	Oct	281	1400				No L_{in}
	Nov	329	1800	to	330	1800	No radiation data—power outage
		331	300				No L_{in}
1984	Mar	70	100	to		900	No radiation data
		71	2200	to	72	1100	No radiation data

Year	*Month*	*J.D.*	*Time*	*to*	*J.D.*	*Time*	*Missing parameter*
1984	Apr	95	1100	to		1300	No L_{in} (1 of 2)
		105	200	to	107	1200	No radiation data
	May	132	2100	to	136	1500	No L_{in}
	Jul	193	2000	to		2400	No radiation data—power outage
	Aug	226	1000				No L_{in}
		227	1100				No L_{in}
		230	1000	to		1600	No L_{in}
		231	1000	to		1500	No L_{in}
		233	900	to		1200	No L_{in}
	Sep	270	700	to		1000	No radiation data
	Dec	344	2300	to	345	1100	No radiation data—tape ran out
		363	1600				No radiation data—power outage
1985	Feb	58	1800	to	59	1300	No radiation data
	Apr	120	1100	to		1400	No K_{ref}, then mounted upright
	May	123	2400				No L_{in}
	Jun	155	1000				No L_{in}
		161	1000	to		1500	No L_{in}
		162	1000	to		1300	No L_{in}
		166	800	to		1600	No L_{in}
		168	1200	to		1500	No L_{in}
		170	1200	to		1700	No L_{in}
		171	1000	to		1600	No L_{in}
		172	1000	to		1500	No L_{in}
		173	900	to		1500	No L_{in}
		174	1100	to		1500	No L_{in}
		175	1100				No L_{in}
		175	1500				No L_{in}
		180	1300	to		1600	No L_{in}
		181	800				No L_{in}
		181	1000				No L_{in}
	Jul	182	1100	to	183	900	No radiation data
		184	2000				No radiation data
	Nov	312	1200				No L_{in}
		317	1400	to		1800	No L_{in}
		324	1100	to		1700	No K_{in}
	Dec	350	500	to		1100	No radiation data
1986	Jan	24	1200	to		1400	No L_{in}
	Feb	43	1400				No L_{in}

Year	Month	J.D.	Time	to	J.D.	Time	Missing parameter
1986	Mar	73	1300	to		1700	No L_{in}
		76	1100	to	77	1400	No L_{in}
		78	1500				No radiation data
		78	1600	to	79	1700	No L_{in}
		80	1400	to	84	1200	No L_{in}
	Apr	93	1300	to	94	1600	No L_{in}
	May	121	100	to	128	1400	No data
		139	1400	to	144	2200	Sporadic radiation data
		144	2300	to	151	2400	No data
	Jun	152	100	to	177	1500	No data
		180	1700				No data
		180	1800	to	181	1500	No K_{in}
		181	1000	to		1500	No data
	Jul	182	100	to		1600	No radiation data
		182	1000	to		1300	No data
		182	1500				No data
		207	1600	to	212	2400	No L_{in}
	Aug	219	800	to	224	100	No data
		224	1000	to		1600	No radiation data
		235	1700	to	238	1700	No data
		241	1200	to	243	2400	No data
	Oct	274	100	to	281	1900	No data
		301	800	to	303	1200	No data
		304	700	to		1300	No data
	Nov	313	2200	to	334	2400	No data
	Dec	335	100	to	338	1300	No data
		354	1700	to	355	200	No data
		355	700	to	358	1000	No data
1987	Jan	1	100	to	6	1400	No K_{in}
		14	1500				No data
		15	100				No data
		15	400	to		2400	Sporadic data
		16	100	to	21	1200	No data
	Feb	33	1500	to	34	800	No data
	Mar	90	1600	to		2400	No data
	Apr	91	100	to		1300	No data
		93	1300	to		1500	No data
		119	100	to	120	2400	No data

Year	*Month*	*J.D.*	*Time*	*to*	*J.D.*	*Time*	*Missing parameter*
1987	May	121	100	to	125	900	No data
		121	100	to	141	1500	No L_{in}
		148	2000	to	151	2400	No data
	Jun	152	100	to	160	1500	No data
		161	1700	to	162	1200	No L_{in} 2
	Jul	188	1700	to		1900	No L_{in}
		189	1100	to		1700	No L_{in}
		197	1000	to	198	1300	No data–power outage
		199	1900				End L_{in} 2
	Aug	214	1300	to		2300	No L_{in}
		219	1800	to		2400	No L_{in}
		242	1900	to	243	1600	No data
	Sep	248	1600	to	260	1200	No L_{in}
		261	1200	to	264	1800	No data
	Oct	277	1700	to	285	1600	No data
		287	1600				One K_{in} end for month
		294	1600	to	304	2400	No data
	Dec	335	100	to	346	100	No data
1988	Jan	1	100	to	4	1600	No L_{in}
		1	100	to	8	1600	No L_{out}
		13	1300				No L_{in}
		14	1400	to	18	1700	No L_{out}
	Feb	32	100				No L_{in}
		32	100	to		300	No L_{out}
		51	600	to		800	No L_{in} or L_{out}
		57	1300	to	60	2400	No data
	Mar	61	100	to		1500	No data
	Apr	97	100	to	121	2400	No L_{out}
		99	100	to	121	2400	No K_{ref}
		103	2200	to	121	2400	No data
	Jun	158	1300				No data
		164	1600	to	182	2400	No data
	Sep	245	100	to	257	1100	No data
	Oct	287	1400				No data
		291	1500	to	299	1100	Most data missing
	Nov	310	1200	to	335	2400	No data

Year	Month	J.D.	Time	to	J.D.	Time	Missing parameter
1989	Dec	336	100	to	366	2400	No radiation data
		336	100	to	358	1300	No data
		361	300	to	363	1600	No data except JD 361 300–700
1989	Jan	1	100	to	6	1700	No L_{in} or L_{out}
		1	100	to 9	9	1400	No K_{in} or K_{ref}
		1	1900				No data
		12	1200				No radiation data
		19	1400	to	25	1400	No data
		27	100	to		1400	Some missing data—printer malfunction
	Feb	38	1500				No radiation data
		38	1800				No L_{in} or L_{out}
		41	1600	to		1800	No radiation data
		55	1700				No *WD*, *PPT*, *S*, radiation data
		55	1800	to	58	1400	No data
	Mar	83	1300	to		2100	No data
	Apr	96	1300				No data
	May	131	1600	to		1800	No L_{out}
		138	1300	to	151	2400	No L_{in} and L_{out}
		150	1400	to	151	2400	No K_{in}
	Jun	164	1000				No data
		166	1300	to		1500	No data
		172	1400				No data
		174	1200	to	178	1500	No data
	Jul	202	1100	to		1600	Sporadic data
	Aug	221	1500				No radiation data
		223	1200	to		1500	No radiation data
1990	Jan	1	100	to	9	1600	No L_{in}
		1	100	to	16	1700	No L_{out}
		12	1500				No data
		16	1600	to	18	1600	No K_{ref}
	Feb	32	1600				No K_{ref} or L_{out}
	May	124	1800	to	125	100	No L_{out}
		136	500	to		1600	No L_{out}
	Jun	154	1700	to	166	1600	No L_{in}
		180	1400	to	181	2400	No L_{in}
	Jul	182	100	to	212	2400	No L_{in}, L_{out}

Year	*Month*	*J.D.*	*Time*	*to*	*J.D.*	*Time*	*Missing parameter*
1990	Aug	213	100	to	243	2400	No L_{in}, L_{out}
		225	1800	to		2100	No data
	Oct	274	1400	to		1600	No radiation data
		277	1100	to	284	1500	No radiation data
		278	1300				No data
		285	1100				No K_{ref}
		291	1100	to		1300	No K_{in}
		292	1000				No data
		292	1200				No data
		292	2100	to		2400	No data
		297	1200				No data
		298	1200	to		1500	No data
		299	1400	to		1600	No data
	Nov	305	100	to	334	2400	No L_{in} or L_{out}
		312	1100				No data
		312	1200				No radiation data
	Dec	335	100	to	337	1500	No L_{in}
		335	100	to	341	1500	No L_{out}
		341	1400				No radiation data
1991	Jan	4	1700	to	15	1600	L_{out} sporadic
		15	1400	to		1600	No radiation data
		24	900	to		1700	Sporadic data
		24	1000	to	29	1300	No *WS* or radiation (some K_{ref}) data
		28	1100				No data
		29	1200				No data
	Mar	64	1900	to	66	1500	No L_{in}
	Apr	92	1400	to	120	2400	No L_{in}
	May	121	100	to	151	2400	No L_{in}
		121	1300	to	130	1600	No K_{in}
	Jun	163	1600	to	181	2400	No L_{in}
	Aug	213	100	to	342	2400	No L_{in}
	Oct	274	100	to	304	2400	No L_{in}
	Nov	305	100	to	334	2400	No L_{in}, L_{out}
	Dec	335	100	to	365	2400	No L_{in}
		335	100	to	358	1600	No L_{out}
		335	100	to	364	1600	No K_{ref}
		353	800	to		1200	No K_{in}
		377	800	to		1300	No K_{in}

Year	Month	J.D.	Time	to	J.D.	Time	Missing parameter
1992	Jan	10	800	to		1300	No K_{in}
		15	800	to		1300	No K_{in}
		20	800	to		1400	No K_{in}
		21	800	to		1400	No K_{in}
		22	800	to		1200	No K_{in}
		27	800	to		1300	No K_{in}
		28	800	to		1600	No K_{in}
	Feb	32	100	to	48	1445	No L_{in}
	May	149	1100				No data
	Jun	164	1500	to	182	2400	No L_{in} or L_{out}
	Jul	153	100	to	213	2400	No L_{in}, L_{out}
	Aug	214	100	to	244	2400	No L_{in}, L_{out}
		240	1300				No data
	Sep	245	100	to	260	1600	No L_{in}
		267	900	to	274	2400	No L_{in}
	Oct	296	1200				No radiation data
	Nov	306	100	to	335	2400	No L_{out}
		306	100	to	314	1800	No L_{in}
		317	1700				No L_{in}
		325	1400	to	330	1400	No radiation data

KEY:

K_{in}	Incoming solar
K_{ref}	Reflected solar
L_{in}	Incoming terrestrial
L_{out}	Outgoing terrestrial
Q_{in}	Total incoming solar and terrestrial
PT	Plate temperature for Q_{in}

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A long-term (24-year) database of solar and terrestrial radiation, as monitored in northern Vermont, has been compiled. This extensive database is a result of cooperative efforts among many different government agencies. This report summarizes the present status of the solar and terrestrial radiation database, the instrumentation and calibration, and methods of data measurement, acquisition and analysis.

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